Fermi National Accelerator Laboratory

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Radiation Hardness of 3HF-Tile/02-WLS-Fiber Calorimeter

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Abstract

The radiation hardness of a 3HF-tile/O2-WLS-fiber calorimeter with two different tile/fiber patterns has been studied. Two calorimeter modules were irradiated up to 10 Mrad with the BEPC 1.3 GeV electron beam. The radiation damage of these modules is compared with our previous measurements from SCSN81-tile/BCF91A-WLS-fiber modules [1,2]. The longitudinal damage profiles are fitted as a function of depth.

1. INTRODUCTION

From our previous studies on irradiation of 8 scintillator tile/wavelength-shifter (WLS) fiber modules, we concluded that:

(1) The scintillator tile/WLS fiber technique can be used in the SDC barrel calorimeter. The existing commercial scintillator (SCSN81) and WLS fiber (BCF91A) are suitable for the SDC barrel calorimeter [1].

(2) The Multi-Fiber Module (MFM) structure increases the radiation hardness of the tile/fiber system [2].

The dose at the inner edge of the endcap calorimeter is 570 krad/year and one must design assuming that the SSC may operate at a luminosity of 10^{34} /(cm^2 sec). It is, therefore, necessary to study how to decrease the radiation damage by selecting suitable file/fiber materials or by trying different optical patterns. After irradiation, polystyrene based scintillators are known to absorb more at short wavelengths than long wavelengths, resulting in a decrease in light yield [3]. Therefore, a scintillator which emits longer wavelength light is expected to be more radiation hard than one which emits at shorter wavelengths. The goal of this study is to provide a proof that a 3HF/O2 tile/fiber calorimeter and a MFM structure will work in the SDC endcap region. We believe that the goal has been realized.

2. EXPERIMENTAL SETUP AND IRRADIATION

(1) Modules

A standard tile module consists of 21 Pb plates of absorber, interspaced with 20 scintillator tiles. The Pb plate is 5 mm thick and 12.7 cm x 12.7 cm. The scintillating tile is a polystyrene-based, green emitting scintillator, commonly called 3HF, which is manufactured by Kuraray Co. The scintillating tile was 2.5 mm thick and 11 cm x 11 cm in area. The light output from the scintillator is collected using O2 wavelength shifter fiber (1 mm diameter, shifts from green to orange) made by Kuraray Co. The WLS fibers were embedded in the files using key-hole shape grooves. The WLS fibers were spliced to high transmittance clear fibers which were directly connected to a photomultiplier tube (PMT) with no depth segmentation. The edges of the tiles were painted with a reflective coating paint, BC620. The tile was wrapped with aluminum foil and marvel guard paper to optimize the light output and protect the tiles.

Tiles in Module #9 had a single WLS fiber in each tile in a groove pattern of the alpha shape (see Figure 1). Module #10 had 9 straight line fibers embedded per tile and was called the Multi-Fiber Module (MFM). The setup is shown in Figure 1.

(2) Radiation Source

The BEPC (Beijing Electron Position Collider) provided a 1.3 GeV electron beam for irradiating the modules.

(3) Dose Monitoring

The BCT (Beam Current Transformer) measures the integrated electron flux. The conversion from incident electron flux to dose in Mrads at EM shower maximum is calculated by using a conversion factor of;

$$1 \text{ rad} = 3 * 10^6 \text{ electrons/cm}^2.$$

Therefore, 1 Mrad is equivalent to $3 * 10^{12}$ electrons/cm^2 at 1.3 GeV incident on the front surface of the modules.

(4) Irradiation

The two modules were mounted on a moveable table, which is motorized and capable of motion in both the horizontal and vertical directions in order to provide a uniform irradiation. The irradiating steps were first 0.2 Mrad, 0.3 Mrad, 0.5 Mrad, then 0.5 Mrad/step up to 6 Mrad, and finally four steps of 1 Mrad from 6 to 10 Mrad total dose. The irradiation was taken from October 31, 1992 to November 15, 1992, a step per day.

3. DATA TAKING AND ANALYSIS

(1) Data collection

After every irradiating step was finished, the table was immediately moved away from the beam line. After about an 8 hour wait, the measurement of radiation damage was accomplished using a moving radioactive source (Cs^{137}, 6.8 Ci). The source had a remotely actuated driver capable of pushing a wire carrying a radioactive source through any one of 26 tubes which pass through the module, 6 longitudinal (L1:L6) and 20 transverse (T1:T20) tubes. The PMT current was read out by an IBM/PC and a CAMAC data acquisition system via a DSP2032 autoranging scanning DVM.

(2) Pedestal and calibration

Pedestal data (sum of the pedestal from the electronics readout and the dark current of the PMT) was taken before and after every source measurement by sampling 200 times while the source was in the garage. The pedestal was subtracted from the source data. The gain of the PMT was monitored by a 100 nCi Am^{241} source which was embedded in the cookie near the photocathode viewed by a small piece of BC408 scintillator. The output pulseheight from the Am^{241} was very small compared to the source current and was used to monitor the stability of PMT gain. For relative calibration, the source data taken before irradiation, which was called pre-irradiation data, is defined to be 0 Mrad data. The 0 Mrad data was taken from each transverse and longitudinal tube for each module and was used to normalize the source data after irradiation.

4. RESULTS AND DISCUSSION

(1) Radiation damage at shower maximum

The transverse uniformity and light yield of the tile located at EM shower maximum (tile #3) was measured as a function of total dose for both the single fiber module (SFM) and the MFM. Figure 2(a) shows the light yield scanned across the tile surface at different total doses for the SFM (Module #9). Data from the MFM (Module #10) is shown in Figure 2(b). The absolute light output from the MFM is much larger than the SFM. The uniformity of response on the file surface does not seem to have large degradation but SFM damages faster than MFM.

(2) Depth profile of damage

Figure 3 and Figure 4 show the depth profiles after each step of irradiation for Module #9 and #10. Figure 3(c,d) and Figure 4(c,d) are normalized to the 0 Mrad data while Figure 3(a,b) and Figure 4(a,b) was normalized assuming tile #2 was undamaged.

(3) Annealing (recovery)

After a total irradiation of 10 Mrad, we stopped the irradiation and continued to take data to measure the annealing of scintillators and fibers. Figure 5 shows the annealing of Modules #9 and #10 from a transverse scan. Figure 6 and Figure 7 are the depth profiles of annealing for Module #9 and #10. We found recovery saturated after only 7.5 days of annealing. The light yield after 37.5 days is the same as after 7.5 days of recovery within our measurement error. The light yield ratio at the maximum damaged tile (shower max) after 10 Mrad of irradiation and 7.5 days of annealing is 0.40 for Module #9 and 0.58 for Module #10.

(4) Comparison with previous measurements

Measured data with 3HF tiles and O2 fibers were compared with the previous measurements using SCSN81 tiles and BCF91A fibers [1,2]. The relative outputs at the maximum damaged tile after 6 Mrad of irradiation are listed in Table 1 for Modules #5, 8, 9 and 10. From Table 1, we concluded that 3HF/O2 is more radiation hard than SCSN81/BCF91 and that the MFM is more radiation hard than the SFM. The light yield ratio (normalized to 0 Mrad and tile #20) at shower max is listed in Table 2 for Modules #9 and #10 after irradiation up to 6 Mrad dose, 10 Mrad dose, and 7.5 day annealing after 10 Mrad. Table 2 shows that the MFM structure increases the radiation hardness of the tile/fiber system as previously observed in blue/green combinations of tile/WLS [2].

Table 1: The light yield ratio after 6 Mrad of irradiation.

Module	normalized to	#5	#8	#9	#10
longitudinal	0 Mrad	0.065	0.383	0.404	0.636
scan	0Mrad & T20	0.223	0.470	0.543	0.715
transverse	0 Mrad	0.070	-	0.394	0.641
scan	0Mrad & T20	0.138	0.437	0.524	0.709

Table 2: The light yield ratio after 6 Mrad and 10 Mrad of irradiation and after 7.5 days of recovery for Modules #9 and #10

	Module #	6 Mrad	10 Mrad	after 7.5 days
longitudinal	9	0.543	0.186	0.397
scan	10	0.715	0.369	0.577
transverse	9	0.524	0.145	0.358
scan	10	0.709	0.358	0.561

(5) Data Fitting

The measured damage as a function of total dose has been fit to a simple functional form:

$$\text{Light Yield Ratio} = 1\text{-damage} = A * \exp(-D/Do)$$

where D is the total dose [4]. The damage is defined to be the fractional light loss at shower maximum. The measured light yield ratio from transverse and longitudinal scans is shown in Figures 8 and 9 as a function of total dose. Due to the lack of time for full annealing, the measured data for both Modules #9 and #10 show two different slopes for the regions $D < 6$ Mrad (fully annealed, representing permanent damage to the tile/fiber system) and $D > 6$ Mrad (before complete annealing). The results are summarized in Table 3 along with the data from our previous measurements [1,2].

The fit to the D < 6 Mrad data from Module #10 gives Do (i.e. total dose where 37% of light loss occurs) value of ~ 23 Mrad. Note that the maximum total dose at the EM shower max in the endcap for 100 years running at design luminosity is 57 Mrad.

The damage profiles in depth which are to be used for calibration of the longitudinal non-uniformity due to irradiation were also studied for Modules #9 and #10. Using the functional form described and used in references [4] and [2], the depth profile was fit to the form:

f(X) = exp(-(1/P3)*((P2*X)**(P1-1)*exp(-P2*X))

The data, fitted curve and fit parameters for Modules #9 and #10 are shown in Figures 10 and 11 respectively. The significance of the fit is good, and the fitted values of the parameters are reasonable. The fitted parameters P1, P2 and P3 for both modules are summarized in Appendix 2.

(6) Transverse Uniformity

Using a collimated S_r^{90} source (1.3mm wide, 5mm long), the transverse uniformity of a tile was measured after irradiation. In Figure 12, a uniformity measurement of tile #3 (at shower max, total dose of 10 Mrad) and tile #20 (last layer of the module, total dose 0.5 Mrad) in Module #10 is shown. There is almost no degradation of the transverse uniformity. The transverse uniformity was measured before and after 7 Mrad dose for the alpha pattern tile in both the X and Y directions. Again, no significant transverse nonuniformity was observed due to radiation damage.

6. CONCLUSION

(a) The 3HF scintillating tile and O2 WLS fiber showed a large improvement in radiation hardness.

(b) The Multi-Fiber Module structure increases the radiation hardness of 3HF-tile/O2-fiber system and can be considered as a partial solution for the endcap EM calorimeter.

(c) The measured damage profiles (as a function of total dose and also in depth) were well described by the functional forms from reference [4]. They can be used in a calibration/correction technique to alleviate the damage if longitudinal segmentation of the EM calorimeter is provided.

(d) No significant transverse nonuniformity is introduced by doses up to 10 Mrad.

REFERENCES

[1] L. Hu, et al., "Radiation Damage of Tile/Fiber Scintillator Modules for SDC Calorimeter", SDC-91-119.

[2] S. Han, et al., "Radiation Hardness Test of Tile/Fiber Calorimeter Structure for SDC", SDC-92-365.

[3] A. Bross and A. Pla-Dalmau, "Radiation Induced Hidden Absorption Effects in Polystyrene Based Plastic Scintillator", Fermilab-Pub-90/224.

[4] D. Green and A. Para, "Radiation Damage, Calibration and Depth Segmentation in Calorimeters", Fermilab-FN-565 (1991).

Table 3 LIGHT YIELD RATIO vs. INTEGRATED DOSAGE
AT MAXIMUM DAMAGE(MOST AT TILE #3)

FIT THE CURVE WITH $A * e^{- D / D0}$

	L2 (or (L2+L5)/2)		TRANSVERSE SCAN	
	Norm.to 0Mrad	Norm.to 0Mrad &T20	Norm.to 0Mrad	Norm.to 0Mrad&T20
Module #5 SCSN81/ BCF91A	$0.52*e^{-D/2.57}$ (Fit 0.1-6Mrad	$0.82*e^{-D/4.6}$ (Fit 0.1 - 6 Mrad)	$0.85*e^{-D/1.23}$ (Tile #2)	$0.77*e^{-D/2.91}$ (Tile#2, Norm.T18
			....(Fit 0.1 - 6 Mrad).........	
13day rec.	0.065(6Mr.)-->	0.223(6Mr.)-->	0.070(6Mr.)->	.138(6Mr)-->0.220
Module #8 Multi_Fiber SCSN81/ BCF91A	$e^{-D/7.5}$ (Fit 0.1-1Mrad $0.82*e^{-D/7.849}$ (Fit 1.5-6Mrad	$e^{-D/8.1}$ (Fit 0.1 - 6 Mrad)		$0.99*e^{-D/8.16}$ (Fit 0.1 - 6 Mrad
12 day recovery	0.383(6 Mrad) ---> 0.463	0.470(6 Mrad) ----> 0.491		0.437(6 Mrad) ---->
Module #9 3HF/O2	$0.65*e^{-D/12.2}$ (Fit 0.2-6Mrad	$0.74*e^{-D/20.74}$ (Fit 0.2 - 6Mrad)	$0.67*e^{-D/10.7}$ (0.2 to 6)	$0.78*e^{-D/15.4}$ (Fit 0.2- 6 Mrad)
	$1.19*e^{-D/4.39}$ (Fit 7-10Mrad)	$1.22*e^{-D/5.26}$ (Fit 7 - 10 Mrad)	$1.17*e^{-D/3.99}$ (7 to 10Mrad	$1.45*e^{-D/4.3}$ (Fit 7 - 10 Mrad)
	$2.80*e^{-D/3.0}$ (Fit 6-10Mrad)	$3.23*e^{-D/3.25}$ (Fit 6 - 10 Mrad)	$6.0 *e^{-D/2.18}$ (6 to 10Mrad	$5.0 *e^{-D/2.6}$ (Fit 6 - 10 Mrad
7.5 day RECOVERY	0.131(10Mrad) ---> 0.309	0.186(10 Mrad) ---> 0.397	0.100(10Mrad) ->0.290(TILE3	0.145(10 Mrad) -->0.358(TILE 3)
Module #10 Multi_Fiber 3HF/O2	$0.83e*^{-D/21.6}$	$0.91*e^{-D/25.9}$	$0.83*e^{-D/22.5}$	$0.89*e^{-D/26.74}$
	(Fit 0.2 Mrad -- 6 Mrad data)			
	$1.23*e^{-D/7.36}$	$1.43*e^{-D/7.29}$	$1.27*e^{-D/6.66}$	$1.41*e^{-D/6.76}$
	(Fit 7 Mrad -- 10 Mrad data)			
	$1.83*e^{-D/5.51}$	$1.96*e^{-D/5.75}$	$2.25*e^{-D/4.62}$	$2.34*e^{-D/4.83}$
	(Fit 6 Mrad -- 10 Mrad data)			
7.5 day RECOVERY	0.320(10 Mrad ---> 0.549	0.369(10 Mrad) ---> 0.577	0.290(10Mrad) ->0.544(TILE3	0.328(10 Mrad) -->0.561(TILE 3)

APPENDIX 1
Longitudinal Scan at Max. Damage
For Module#9 and 10, data from (L2+L5)/2

Module #9 (3HF/O2)   Single Fiber

	Normalized to 0 Mrad	Normalized to 0Mrad & Tile#20
0.0	1.000	1.000
0.2	0.666	0.716
0.5	0.636	0.718
1.0	0.584	0.693
1.5	0.548	0.679
2.0	0.526	0.668
2.5	0.517	0.656
3.0	0.508	0.652
3.5	0.494	0.644
4.0	0.470	0.622
4.5	0.445	0.592
5.0	0.426	0.576
5.5	0.415	0.543
6.0	0.404	0.543
7.0	0.247	0.332
8.0	0.185	0.257
9.0	0.147	0.219
10.0	0.131	0.186
7.5 day recovery		
	0.309	0.397

--

Module #10 (3HF/O2)   Multi_Fiber

	Normalized to 0 Mrad	Normalized to 0Mrad & Tile#20
0.0	1.000	1.000
0.2	0.848	0.898
0.5	0.822	0.894
1.0	0.789	0.877
1.5	0.761	0.850
2.0	0.744	0.838
2.5	0.752	0.834
3.0	0.723	0.815
3.5	0.712	0.802
4.0	0.698	0.784
4.5	0.683	0.771
5.0	0.658	0.741
5.5	0.647	0.735
6.0	0.636	0.715
7.0	0.485	0.556
8.0	0.402	0.460
9.0	0.360	0.416
10.0	0.320	0.369
7.5 day recovery		
	0.549	0.577

MODULE #9(3HF/O2)

TRANSVERSE SCAN AT MAX.DAMAGE(TILE 3)
NORMALIZED TO 0 Mras & TILE 20

0.0	1.000
0.2	0.749
0.5	0.758
1.0	0.739
1.5	0.702
2.0	0.656
2.5	0.678
3.0	0.668
3.5	0.652
4.0	0.617
4.5	0.583
5.0	0.557
5.5	0.520
6.0	0.524
7.0	0.296
8.0	0.210
9.0	0.176
10.0	0.145

7.5 day recovery
0.358

NORMALIZED TO 0 Mrad

0.0	1.000
0.2	0.682
0.5	0.660
1.0	0.597
1.5	0.558
2.0	0.511
2.5	0.527
3.0	0.512
3.5	0.498
4.0	0.468
4.5	0.437
5.0	0.416
5.5	0.405
6.0	0.394
7.0	0.212
8.0	0.148
9.0	0.122
10.0	0.100

7.5 day recovery
0.290

MODULE #10 (3HF/O2) MULTI_FIBER,

TRANSVERSE SCAN AT MAX. DAMAGE(TILE 3)
NORMALIZED TO 0 Mrad AND TILE 20

0.0	1.000
0.2	0.878
0.5	0.882
1.0	0.872
1.5	0.836
2.0	0.805
2.5	0.814
3.0	0.793
3.5	0.793
4.0	0.785
4.5	0.752
5.0	0.742
5.5	0.716
6.0	0.709
7.0	0.507
8.0	0.421
9.0	0.369
10.0	0.328

7.5 day recovery
0.561

ONLY NORMALIZED TO 0 Mrad

0.0	1.000
0.2	0.848
0.5	0.828
1.0	0.784
1.5	0.759
2.0	0.732
2.5	0.736
3.0	0.720
3.5	0.712
4.0	0.702
4.5	0.678
5.0	0.666
5.5	0.653
6.0	0.641
7.0	0.456
8.0	0.371
9.0	0.324
10.0	0.290

7.5 day recovery
0.544

Longitudinal Scan at Max. Damage
* For Module #5 and #8, data from L2 *

Module #5 (SCSN 81 + BCF 91A)

	Normalized to 0 Mrad	Normalized to 0Mrad & Tile#20
0.0	1.000	1.000
0.3	0.521	0.794
0.75	0.384	0.689
1.125	0.285	0.628
1.50	0.269	0.613
2.25	0.179	0.503
3.0	0.170	0.422
3.75	0.141	0.375
4.5	0.119	0.300
5.25	0.105	0.294
6.0	0.065	0.223

Module #8 (SCSN 81 + BCF 91A)
Multi_fiber

	Normalized to 0 Mrad	Normalized to 0Mrad & Tile#20
0.0	1.0000	1.0000
0.1	0.9928	0.9967
0.2	0.9593	0.9760
0.4	0.9517	0.9520
0.6	0.9223	0.9218
0.8	0.8926	0.9078
1.0	0.8762	0.8773
1.5	0.6719	0.8126
2.0	0.6475	0.7738
2.5	0.5796	0.7231
3.0	0.5591	0.6813
3.5	0.5221	0.6359
4.0	0.4916	0.6056
4.5	0.4688	0.5874
5.0	0.4264	0.5534
6.0	0.3834	0.4700
12 day recovery	0.4627	0.4911

MODULE #5 (SCSN81/BCF91A)

TRANSVERSE SCAN AT MAX.DAMAGE(TILE2)

	NORMALIZED TO 0 Mrad	NORMALIZED TO 0 Mrad AND TILE #18
0.0	1.005	1.016
0.3	0.505	0.589
0.75	0.380	0.497
1.125	0.263	0.386
1.50	0.282	0.426
2.25	0.186	0.346
3.0	0.184	0.307
3.75	0.144	0.254
4.5	0.133	0.227
5.25	0.104	0.200
6.0	0.070	0.138
13 day recovery		0.220

MODULE #8 (SCSN81/BCF91A)
MULTI_FIBER

TRANSVERSE SCAN AT MAX.DAMAGE(TILE3)
NORMALIZED TO 0 MRAD AND TILE #20

0.0	1.000
0.1	0.980
0.2	0.977
0.4	0.926
0.6	0.918
0.8	0.887
1.0	0.872
1.5	0.825
2.0	0.741
2.5	0.759
3.0	0.662
3.5	0.619
4.0	0.623
4.5	0.591
5.0	0.572
6.0	0.437

APPENDIX 2

FITTING DATA OF DAMAGE PROFILE IN DEPTH

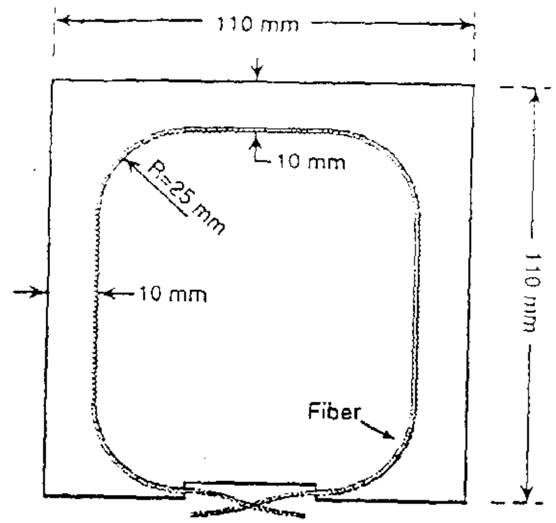
```
F(X)=EXP((-1/P3)*P2*(P2*0.9*X)**(P1-1)*EXP(-0.9*P2*X))
```

MODULE #9

DOSE(Mrad)	P1	P2	P3
0.2	1.5840	0.1936	0.2377
0.5	1.5487	0.1823	0.2344
1.0	1.5052	0.1631	0.2012
1.5	1.5117	0.1783	0.2137
2.0	1.5691	0.1964	0.2168
2.5	1.5793	0.2068	0.2235
3.0	1.5875	0.2148	0.2258
3.5	1.5908	0.2191	0.2236
4.0	1.7230	0.2526	0.2279
4.5	1.7845	0.2714	0.2200
5.0	1.7560	0.2710	0.2061
5.5	1.7485	0.2709	0.2196
6.0	1.8146	0.2973	0.1999
10.0	2.1600	0.4213	0.1727

MODULE #10

DOSE(Mrad)	P1	P2	P3
0.2	1.9830	0.3024	1.0054
0.5	1.7810	0.2512	0.8188
1.0	1.6310	0.2165	0.6792
1.5	1.6025	0.2184	0.5784
2.0	1.7762	0.2791	0.6551
2.5	1.5488	0.2015	0.3894
3.0	1.8186	0.3149	0.6212
3.5	1.9764	0.3537	0.6308
4.0	1.8698	0.3232	0.5321
4.5	2.1487	0.4079	0.6149
5.0	2.0375	0.3728	0.4937
5.5	2.1912	0.4351	0.5378
6.0	2.2668	0.4575	0.5469
10.0	2.4280	0.5075	0.3698



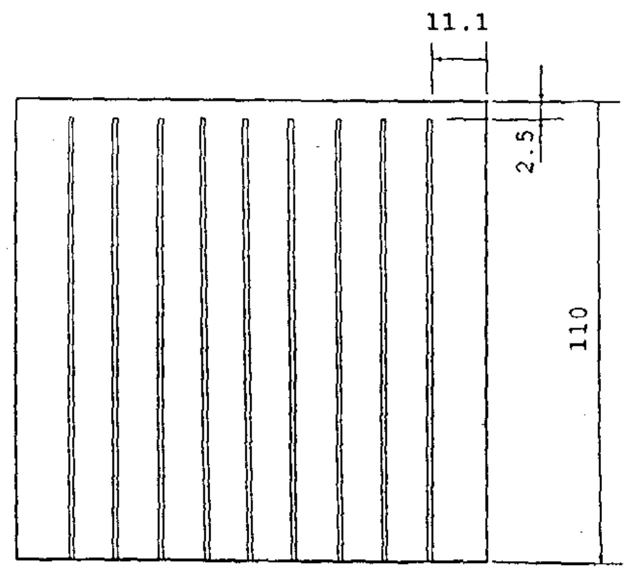
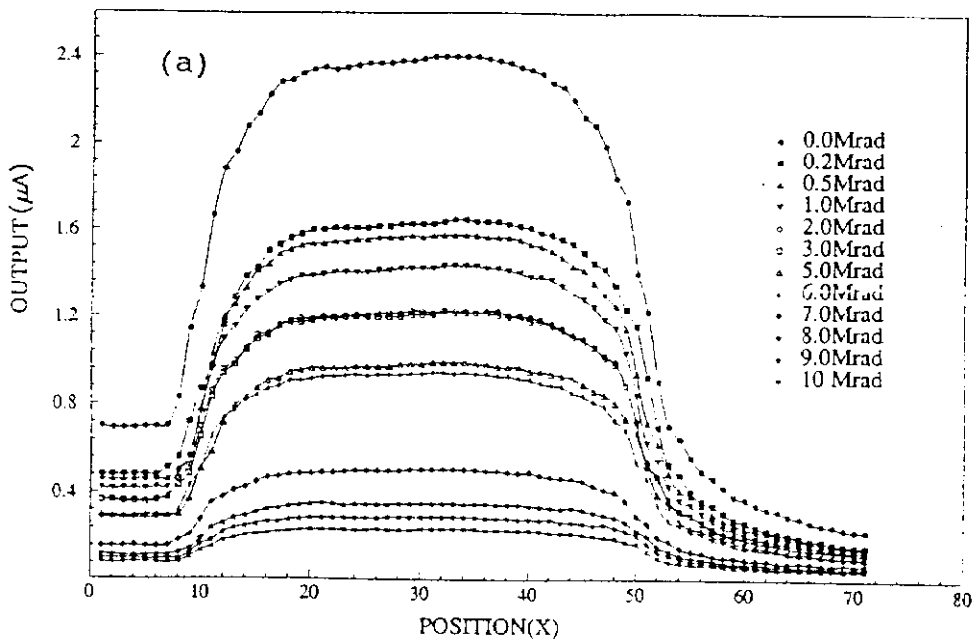


Figure 1. A schematic diagram of tested scintillating tile/fiber assembly.

SINGLE-FIBER M9(3HF/O_2+CLEAR), TILE #3



MULTI-FIBER M10(3HF/O_2+CLEAR), TILE #3

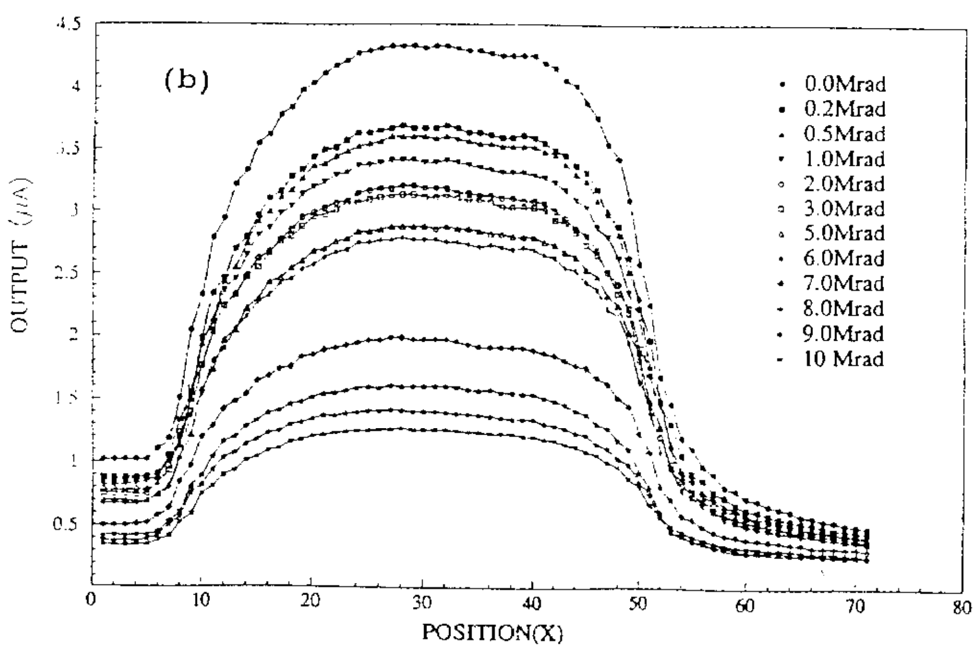


Figure 2. Output light yield at various positions (transverse uniformity) across tile #3 in (a) Module #9 and (b) Module #10 before irradiation.

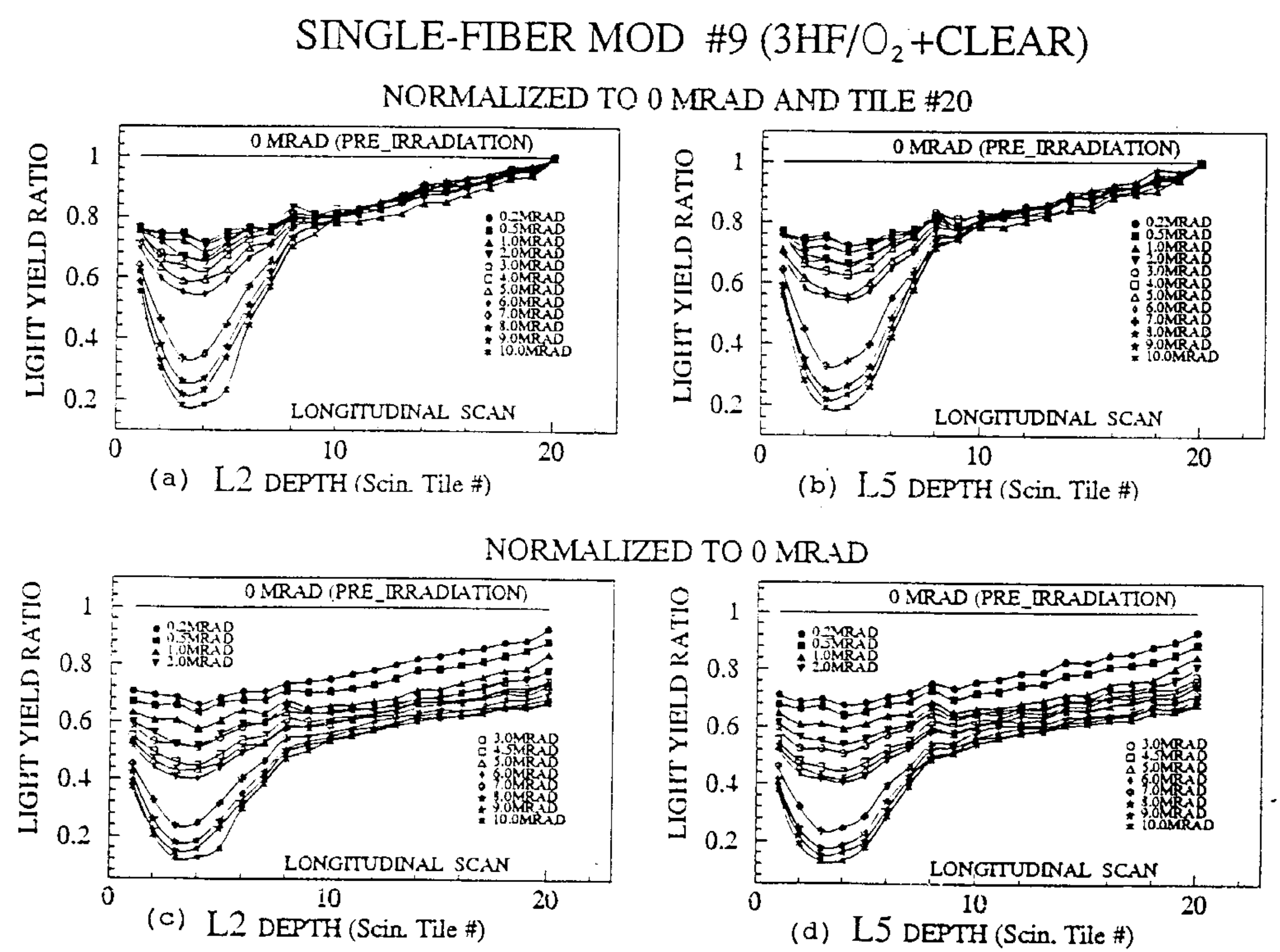


Figure 3. Depth profile for Module #9
(a) L2 scan, normalized to 0 Mrad and tile #20
(b) L5 scan, normalized to 0 Mrad and tile #20
(c) L2 scan, normalized to 0 Mrad
(d) L5 scan, normalized to 0 Mrad

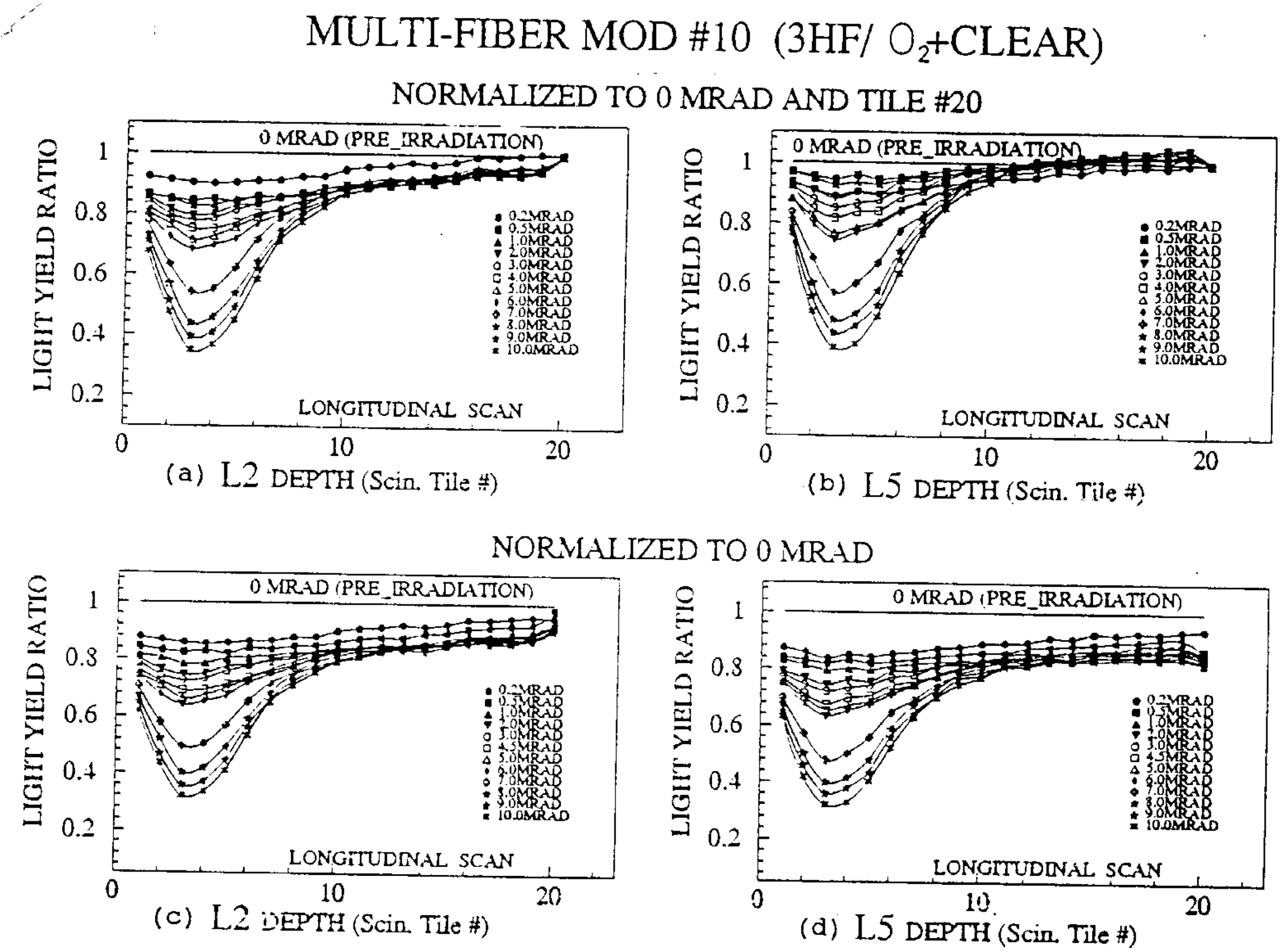


Figure 4. Depth profile for Module #10
(a) L2 scan, normalized to 0 Mrad and tile #20
(b) L5 scan, normalized to 0 Mrad and tile #20
(c) L2 scan, normalized to 0 Mrad
(d) L5 scan, normalized to 0 Mrad

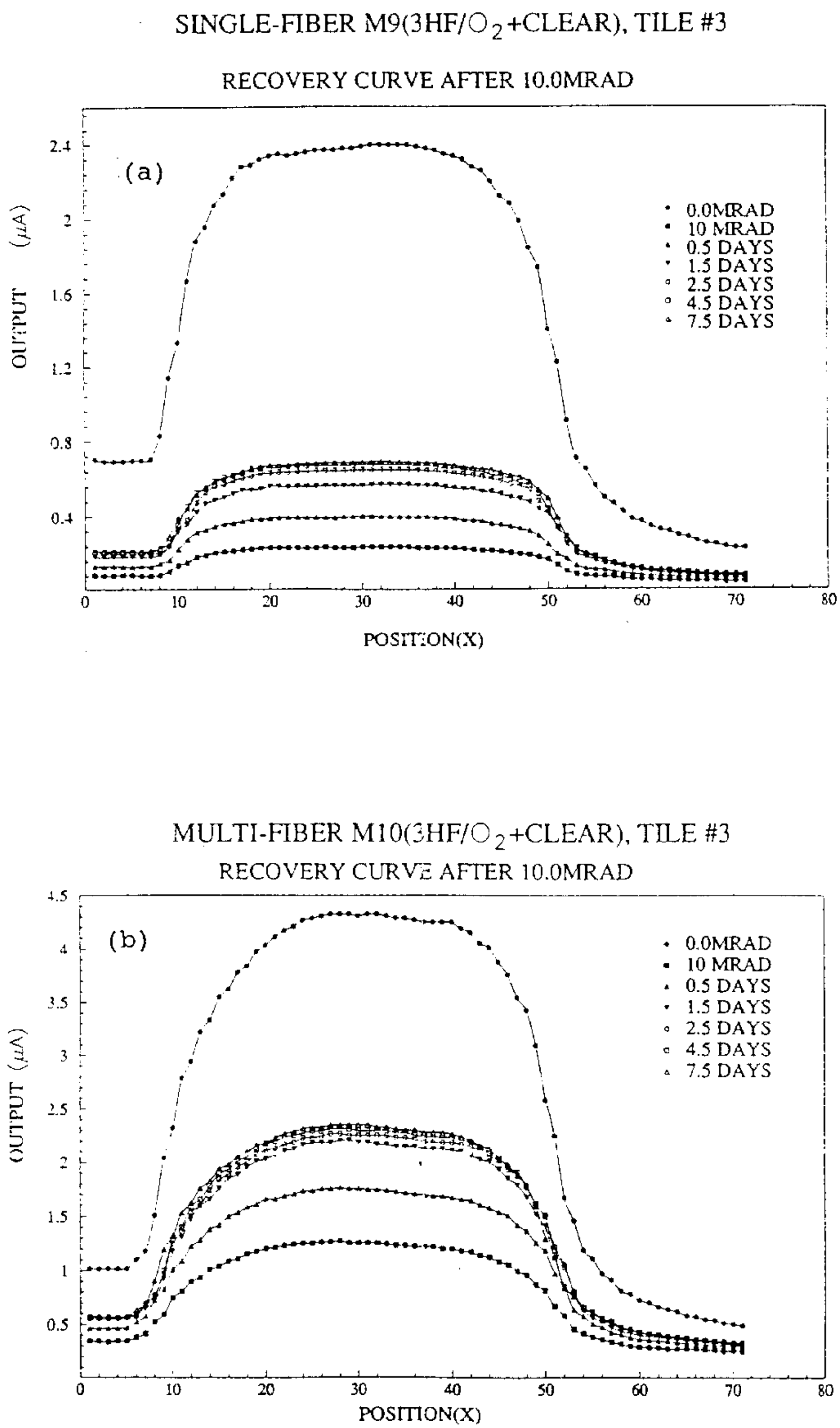


Figure 5. Annealing plots from transverse scan data in (a) Module #9 and (b) Module #10

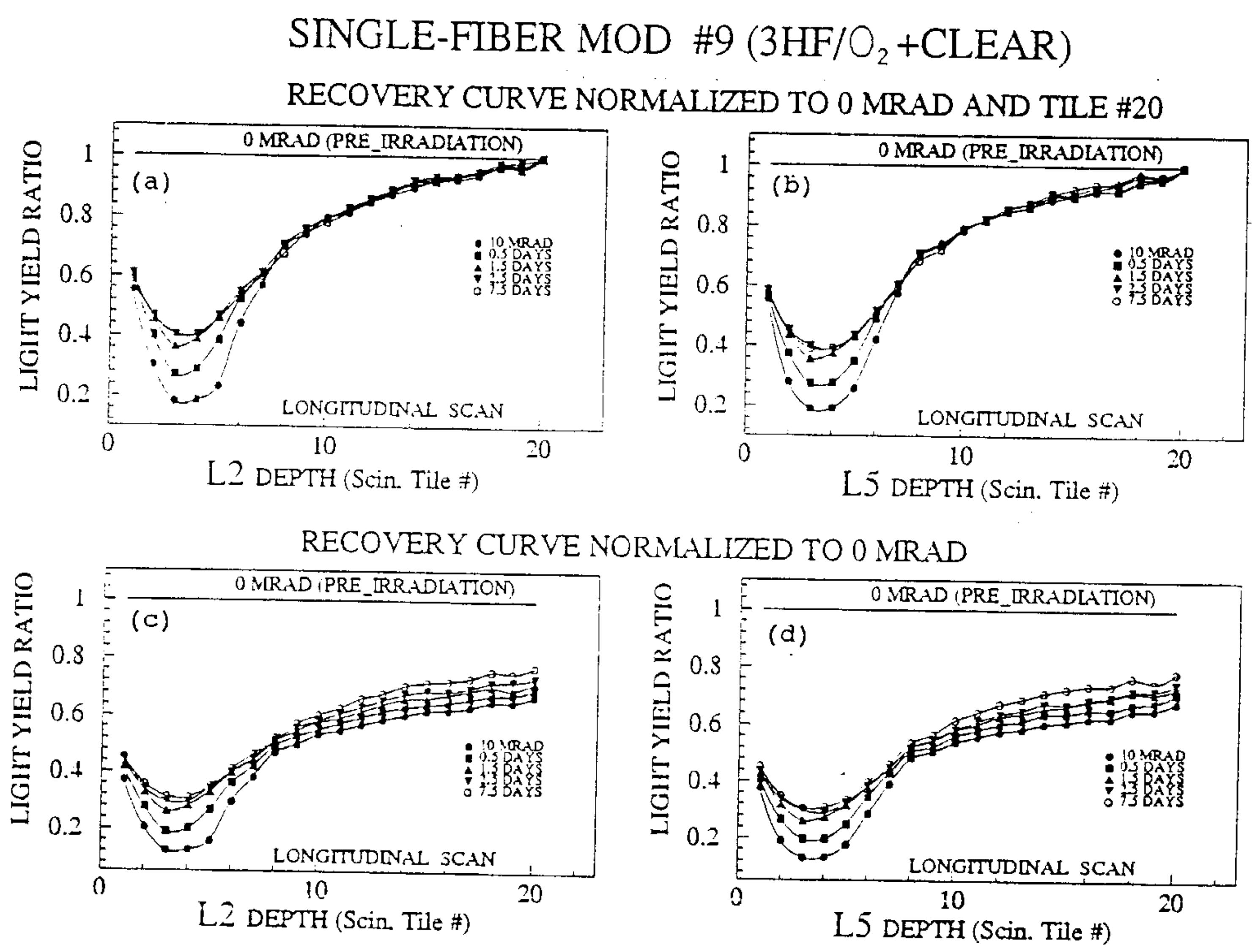


Figure 6. Annealing plots from longitudinal scan data for Module #9
(a) L2 scan, normalized to 0 Mrad and tile #20
(b) L5 scan, normalized to 0 Mrad and tile #20
(c) L2 scan, normalized to 0 Mrad
(d) L5 scan, normalized to 0 Mrad

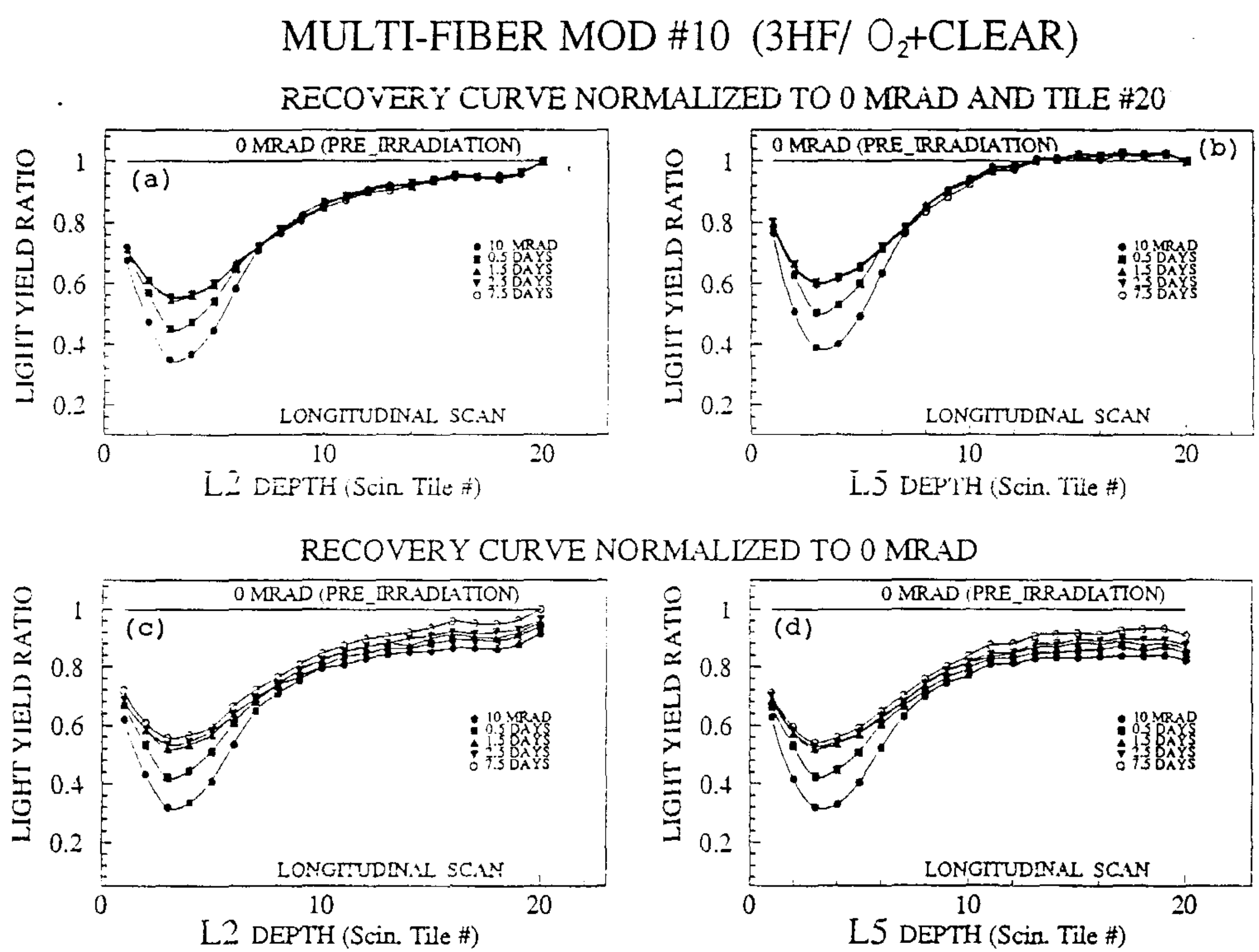


Figure 7. Annealing plots from longitudinal scan data for Module #10
(a) L2 scan, normalized to 0 Mrad and tile #20
(b) L5 scan, normalized to 0 Mrad and tile #20
(c) L2 scan, normalized to 0 Mrad
(d) L5 scan, normalized to 0 Mrad

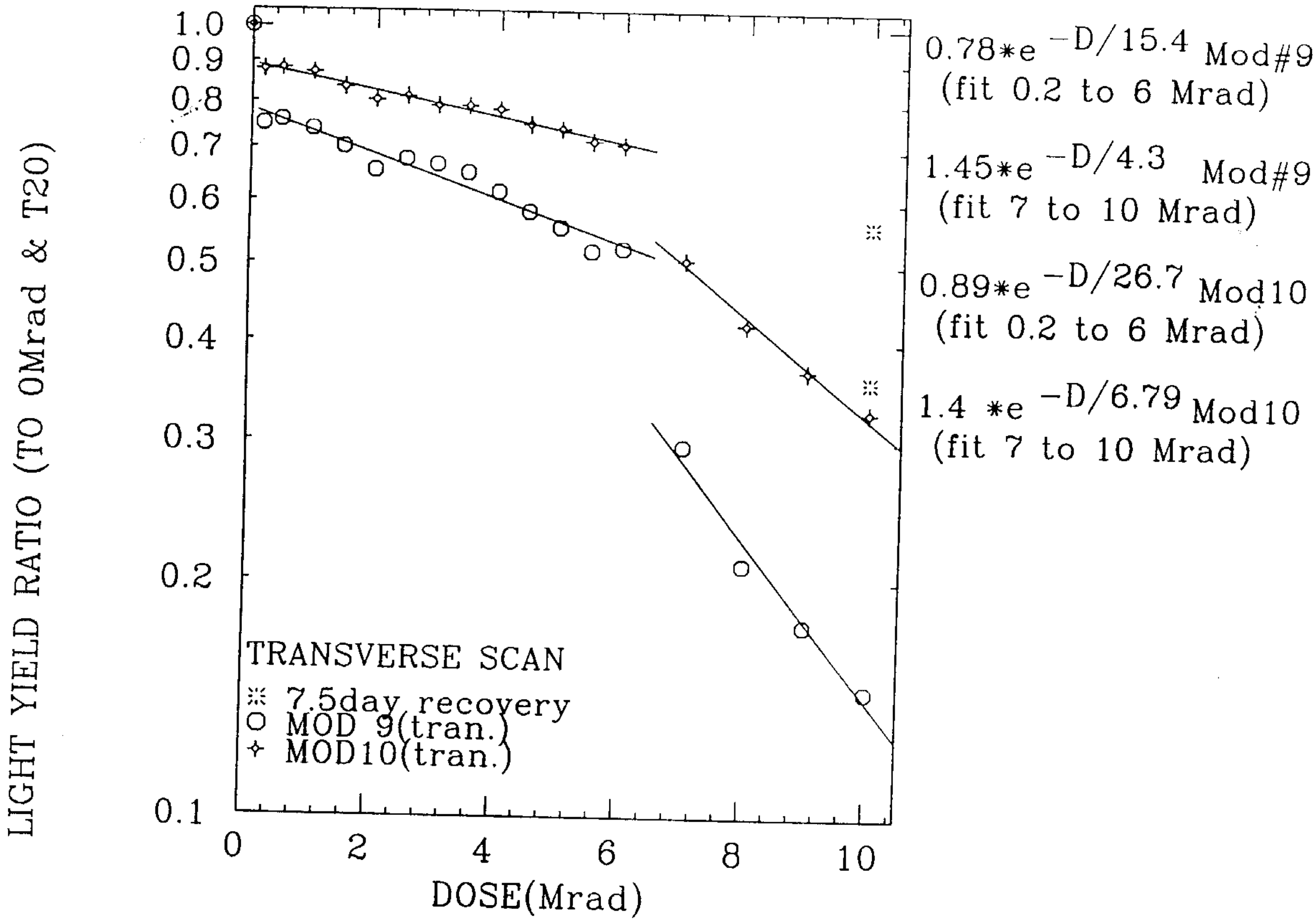


Figure 8. Light yield ratio from transverse scan versus total dose and fit to the data for Modules #9 and #10.

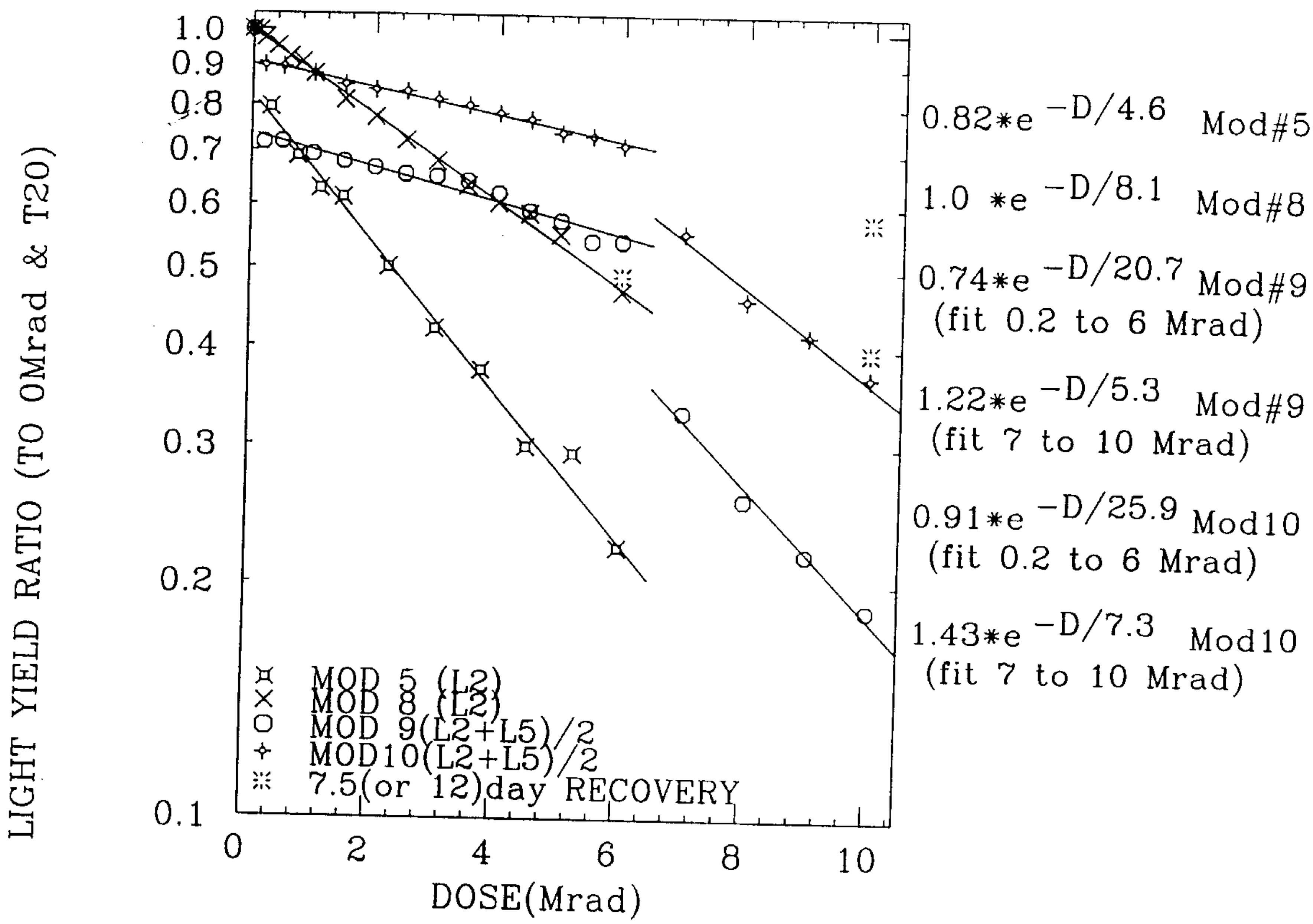


Figure 9. Light yield ratio from longitudinal scan versus total dose and fit to the data for Modules #5, #8, #9 and #10.

SINGLE-FIBER M9(3HF/O2+CLEAR) (L2+L5)/2

FIT FOR VALUE OF NOR. TO 0 MRAD AND TILE #20

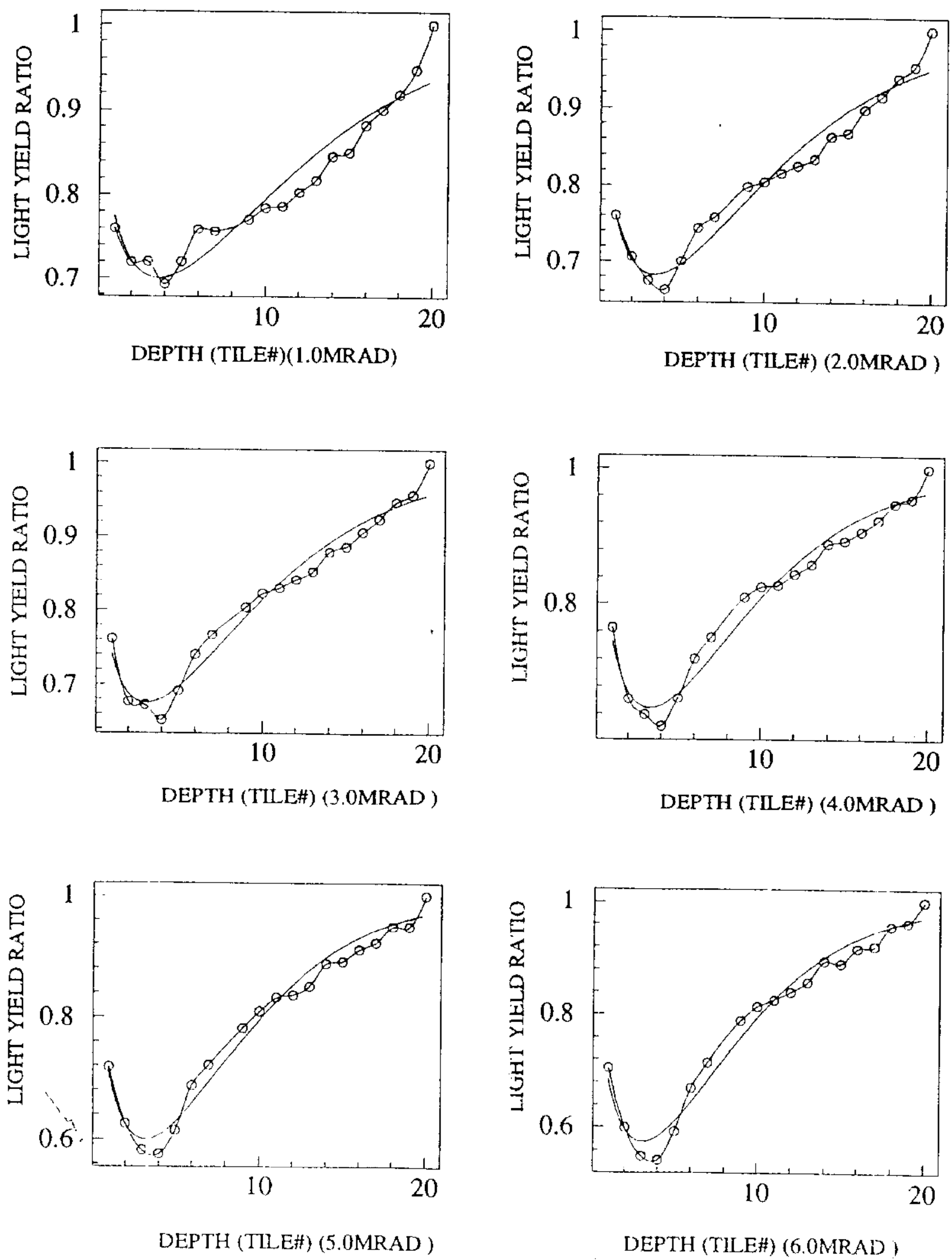


Figure 10. The depth profile, fit and fit parameters at various different doses for Module #9.

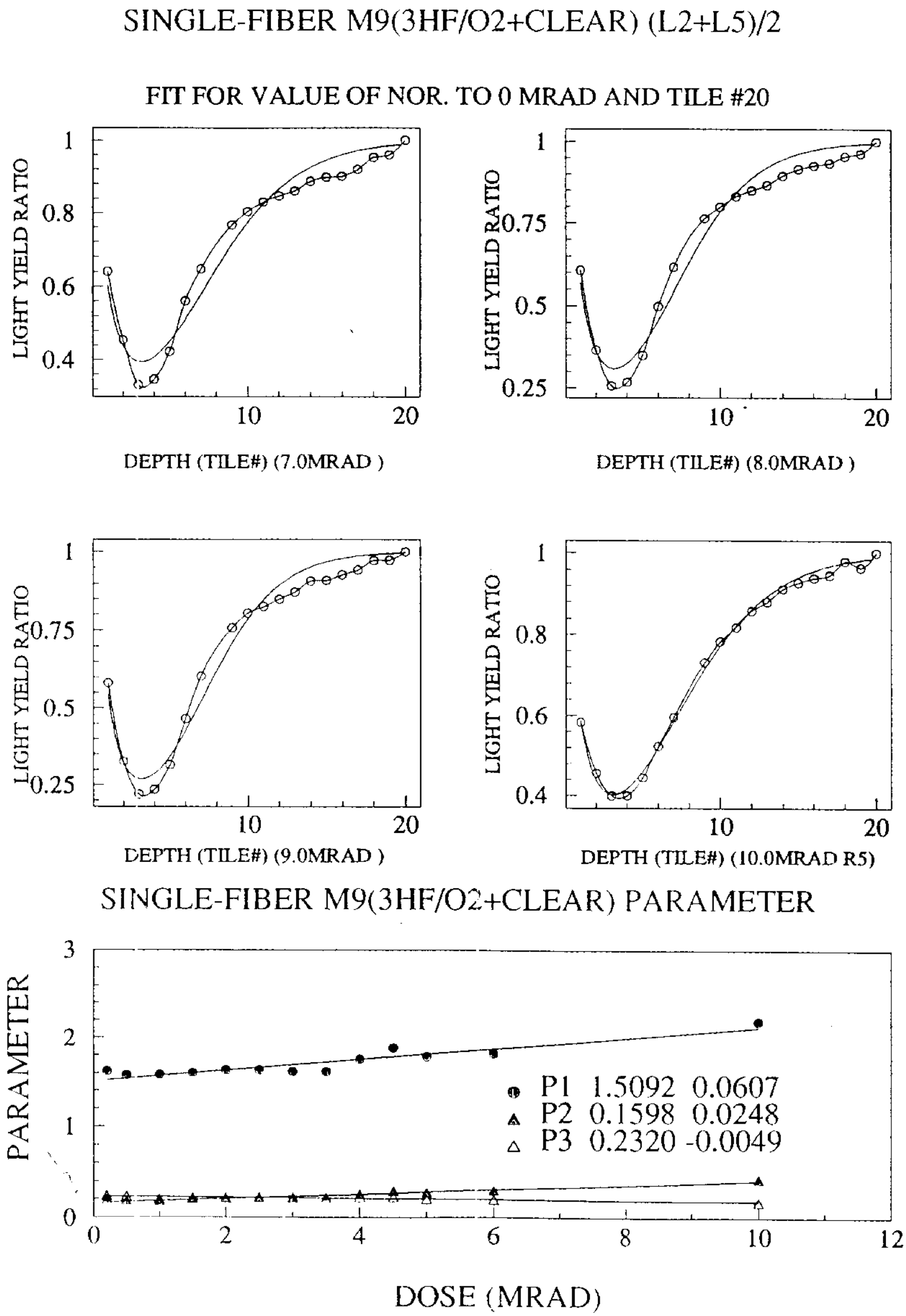

SINGLE-FIBER M9(3HF/O2+CLEAR) (L2+L5)/2
FIT FOR VALUE OF NOR. TO 0 MRAD AND TILE #20
LIGHT YIELD RATIO
DEPTH (TILE#) (7.0MRAD)
DEPTH (TILE#) (8.0MRAD)
DEPTH (TILE#) (9.0MRAD)
DEPTH (TILE#) (10.0MRAD R5)
SINGLE-FIBER M9(3HF/O2+CLEAR) PARAMETER
PARAMETER
P1 1.5092 0.0607
P2 0.1598 0.0248
P3 0.2320 -0.0049
DOSE (MRAD)

Fig.10 (b)

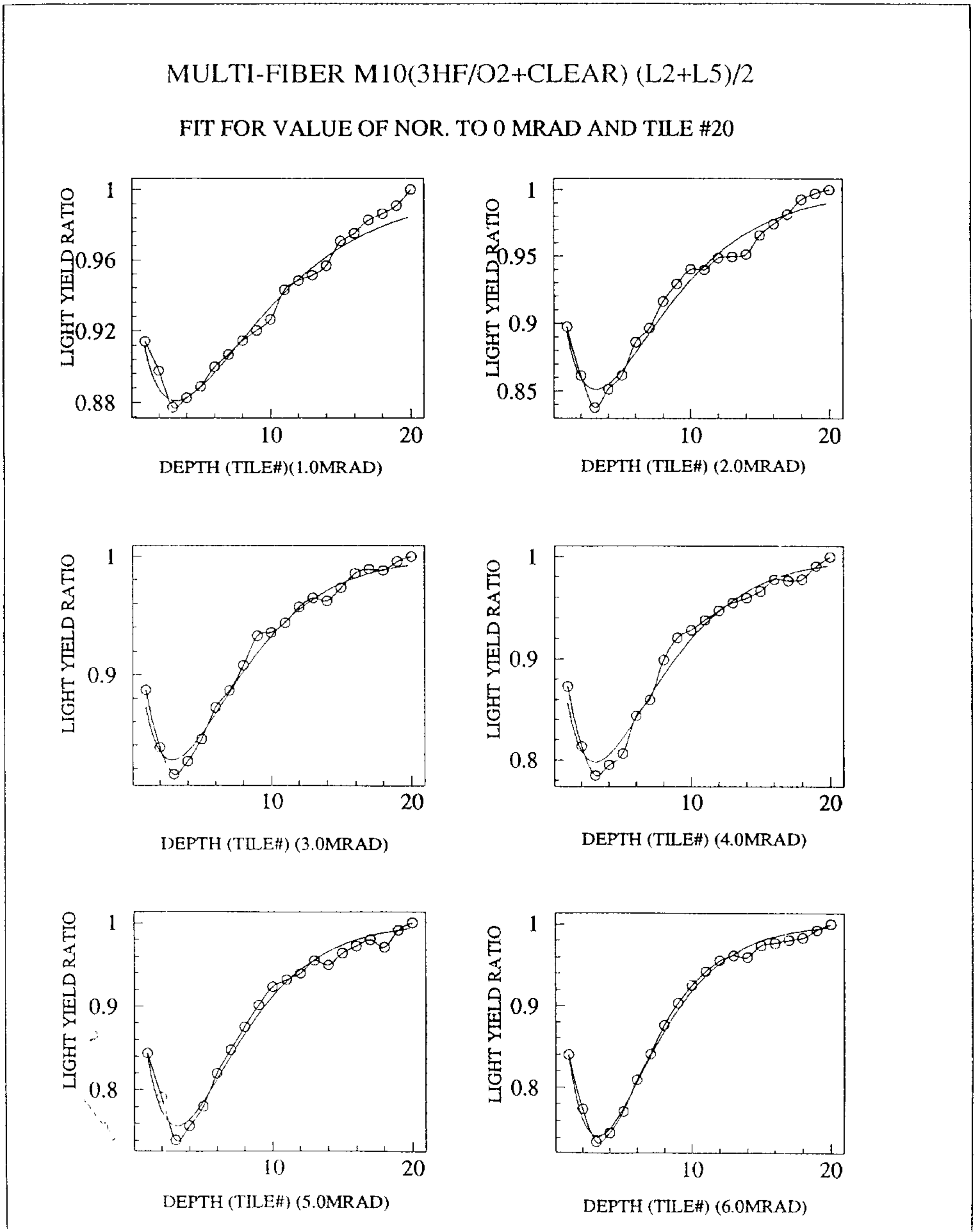


Figure 11. The depth profile, fit and fit parameters at various different doses for Module #10.

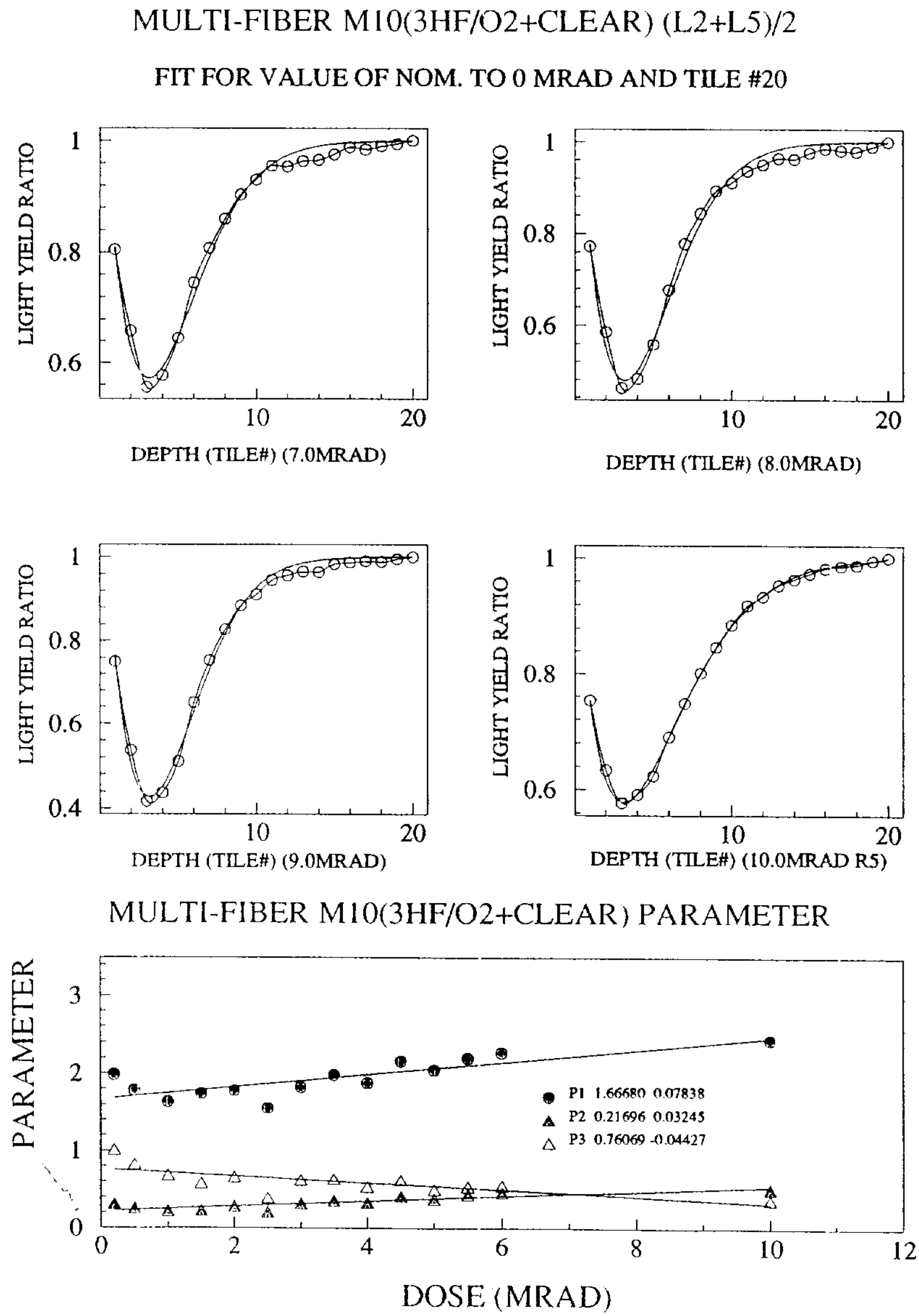
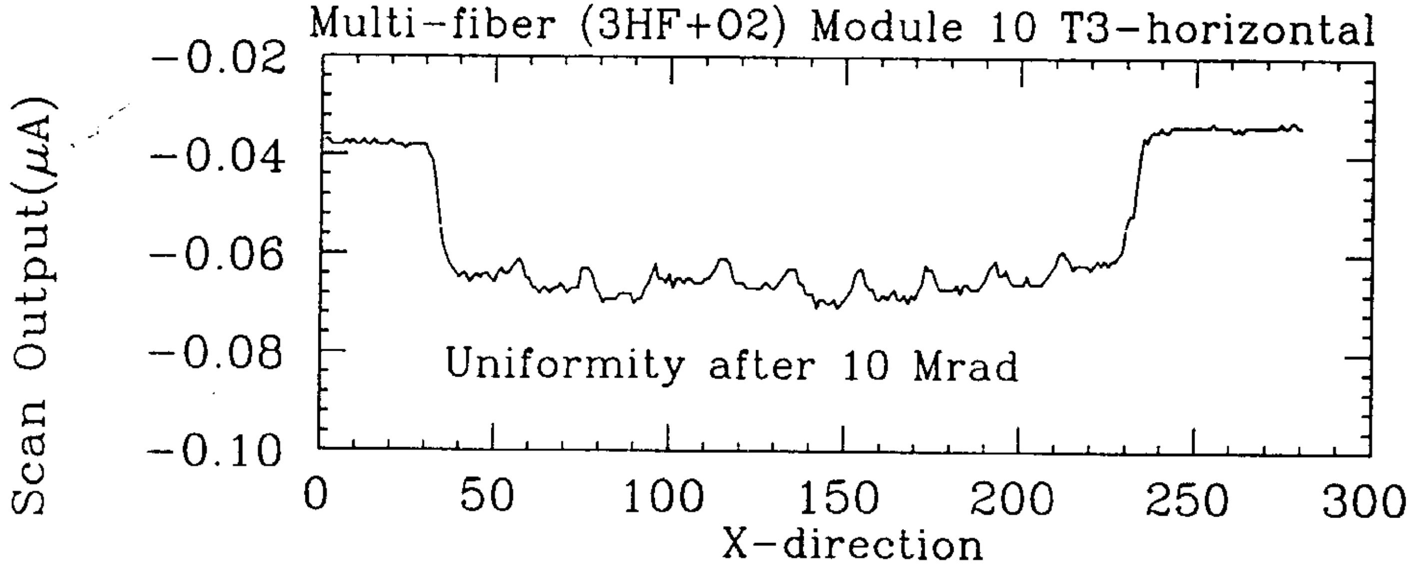

MULTI-FIBER M10(3HF/O2+CLEAR) (L2+L5)/2
FIT FOR VALUE OF NOM. TO 0 MRAD AND TILE #20
LIGHT YIELD RATIO
DEPTH (TILE#) (7.0MRAD)
LIGHT YIELD RATIO
DEPTH (TILE#) (8.0MRAD)
LIGHT YIELD RATIO
DEPTH (TILE#) (9.0MRAD)
LIGHT YIELD RATIO
DEPTH (TILE#) (10.0MRAD R5)
MULTI-FIBER M10(3HF/O2+CLEAR) PARAMETER
PARAMETER
P1 1.66680 0.07838
P2 0.21696 0.03245
P3 0.76069 -0.04427
DOSE (MRAD)

Fig.11 (b)



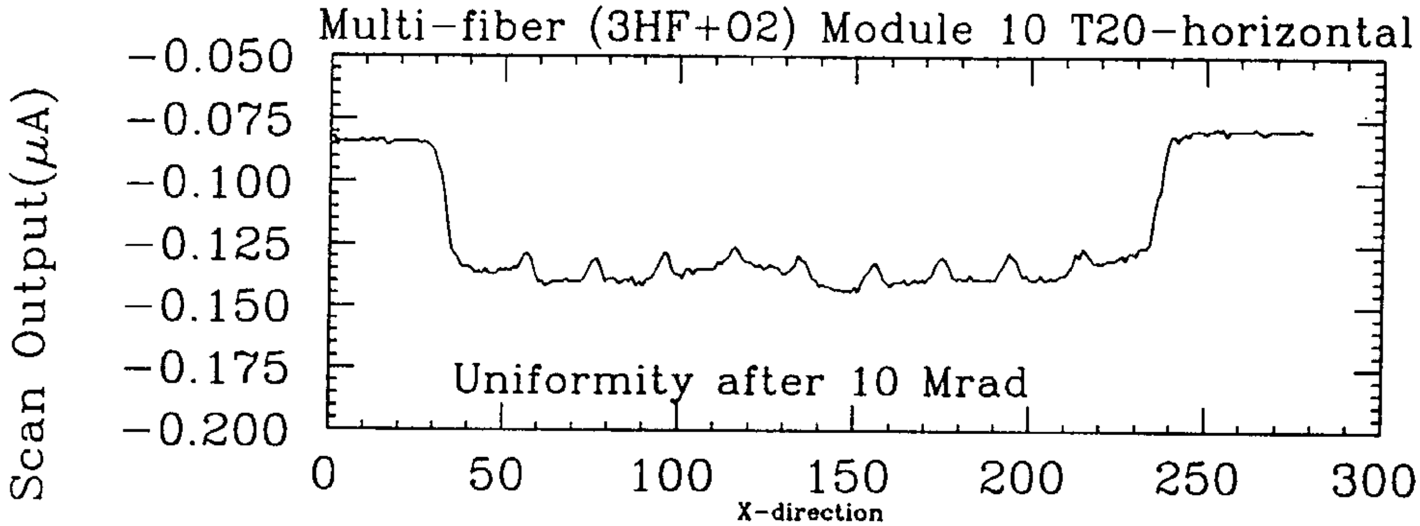
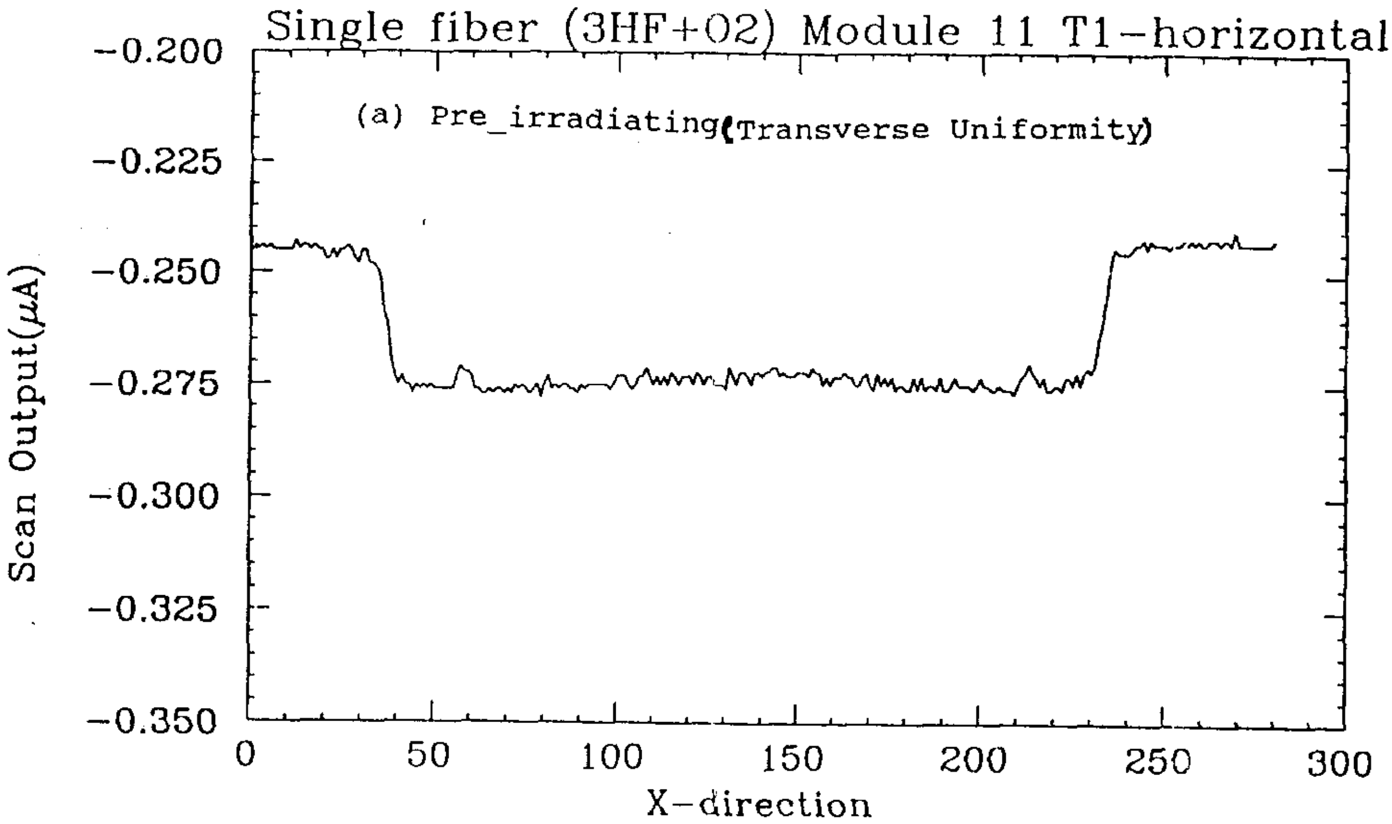


Figure 12. Transverse uniformity of (a) tile #3 and (b) tile #20 in Module #10 (3HF/O2, MFM) after 10 Mrad at shower max.



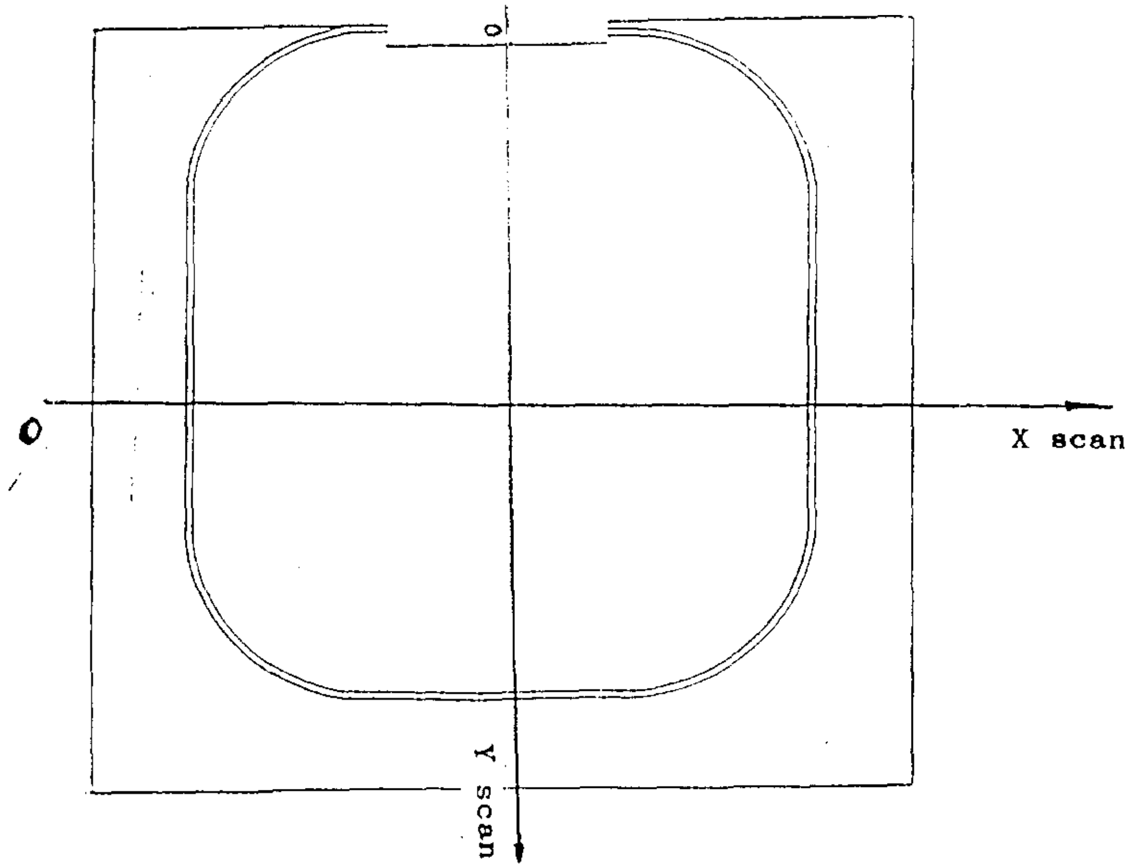
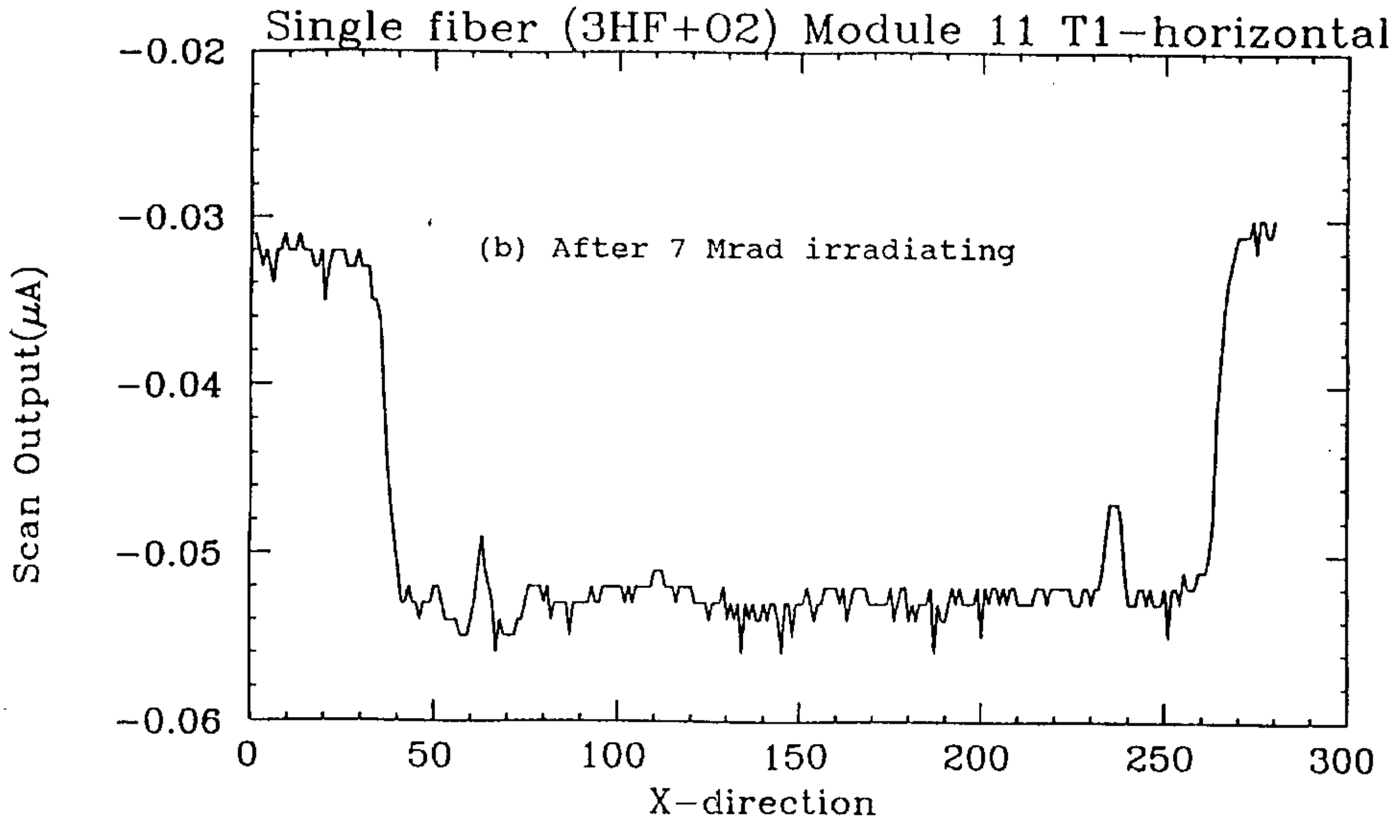


Figure 13. Transverse uniformity of a tile (a) before and (b) after 7 Mrad irradiation in Module #11 (3HF/O2, alpha).


Single fiber (3HF+O2) Module 11 T1-horizontal
(b) After 7 Mrad irradiating
Scan Output(μA)
X-direction
-0.02
-0.03
-0.04
-0.05
-0.06
0
50
100
150
200
250
300

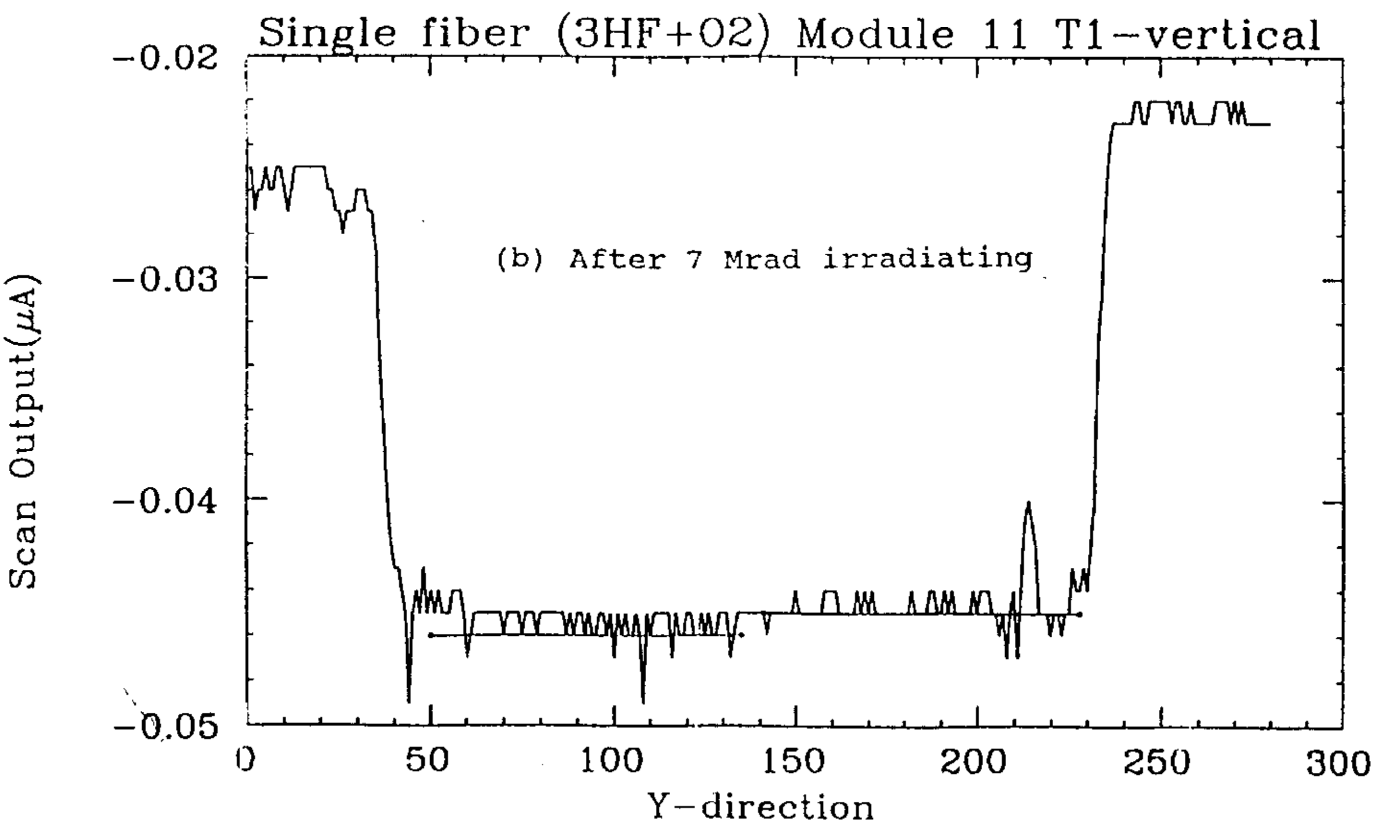

Single fiber (3HF+O2) Module 11 T1-vertical
(b) After 7 Mrad irradiating
Scan Output(μA)
Y-direction
-0.02
-0.03
-0.04
-0.05
0
50
100
150
200
250
300

Fig. 13b